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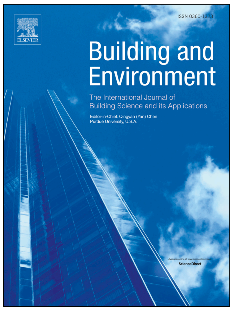

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Evaluating the suitability of standard thermal comfort approaches for hospital patients in air-conditioned environments in hot climates

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Abstract
Hospital patients have the same thermal needs but disparate metabolic levels, and physical/medical conditions. However, the thermal environments of hospitals are often not designed with these distinctions in mind, nor with a particular focus on patients, but based rather on standard comfort methodologies more often used in offices. This paper seeks to confirm if a standard steady-state thermal comfort approach is inadequate, especially in hot climates. The research was conducted on 120 patients during the summer of 2017 in Jeddah, Saudi Arabia, with environmental monitoring of all thermal comfort parameters, alongside estimations of clothing insulation and activity levels for patients in the surgical and medical wards. The data was analysed using simple and multiple regressions, and measures of correlations tests to assess the reliability of the results in addition to t-tests for detecting the differences. The findings revealed a significant difference between the Thermal Sensation Vote (TSV, assessed by patient surveys), and the Predicted Mean Vote (PMV, assessed by physical measurement), with the TSV survey approach failing to identify a unique neutral temperature while the PMV revealed a neutral temperature of 25.6°C. Importantly, the neutral temperature predicted by Griffith's method gave an extremely large range of results, form 16.2°C to 28.8°C (mean=22.7 °C; SD=2.51). The corollary being that using PMV or a non-patient-specific temperature for hospital rooms is a poor idea. Given the known links between hospital environments and recovery outcomes, this result has implications for the design of hospital environments and the setting of national or international standards.

Keywords
Steady-state approach, Griffith's method, Neutral temperature, Thermal comfort.

Nomenclature

T_a	Indoor air temperature, °C
T_r	Mean radiant temperature, °C
T_{op}	Indoor operative temperature, °C
T_n	Neutral temperature, °C

1. Introduction

The design focus of hospitals has shifted from concentrating on functionality to now providing an appropriate and supportive healing environment for patients [1]. "Every day thousands of people experience the pressure of being in a hospital environment. Growing levels of anxiety, depression, stress, agitation, emotional exhaustion, among others, can occur if the surroundings are not appropriate" [2]. Although hospitals accommodate multifunctional zones and different occupants, patients admitted to inpatient wards for medical care still have specific demands of

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the thermal environment based on their individual medical and surgical treatments. Little existing research concentrates on patient subjects in hospitals, supporting the need to explore the complexity of this topic. Thus, standard patient rooms that were occupied during medical treatment were chosen to match the focus of this work. Hwang et al. pointed out that experiencing a comfortable thermal environment enables patients to steady their moods and contribute to their recovery [3] and most likely impacts patients' overall satisfaction with their medical care [4]. Given the confounding factors that might differ from patient to patient, such as age, gender, activity level, clothing, ethnic differences, geographical location, level of acclimatization, expectations, amenities, degree of control, and health and medical condition, it would seem reasonable to expect thermal comfort standards to reflect these, if they are found to indeed be pertinent, and for the methodologies used in thermal comfort research in hospitals to be cognisant of these differences.

Thermal discomfort affects hospital patients on many levels, for example Kaplow and Hardin (2007) pointed out that thermal discomfort in patient rooms had adverse effects on the duration and quality of their sleep [4]. Moreover, sub-optimal air temperature and relative humidity can hinder or advance bacterial development and actuate or deactivate infections. Hence, some regulations set temperature and humidity criteria for health facilities based on contamination control and comfort. An extensive literature review of thermal comfort in hospitals by [3] revealed that, lowering humidity also impacts patients by affecting nose, throat, eyes and skin, especially when the relative humidity decreased to give a dew point below 0°C [5]. Moreover, Johnston and Hunter stated that the indoor temperature needed to be above 21°C to eliminate patient thermal discomfort [6].

1.1. Limitations of current thermal comfort approaches and standards

Two methods have been dominant in discussing thermal comfort over the last half-century:

1. The steady-state approach for environments where occupants have little ability to adapt their levels of dress or room temperature. Fanger (1970) [7], built an exploratory model for this situation combining four physical variables (air temperature, mean radiant temperature, air velocity, and relative humidity) with two human factors (activity level and clothing insulation) to give an objective measurement of Predicted Mean Vote (PMV) [8].
2. The adaptive approach, from Nicol and Humphreys in the 1970s [9], assumes occupants have some control over their environment. This can also be assessed by subjective measurement, by asking occupants to give a Thermal Sensation Vote (TSV), on a scale of -3 (cold) to +3 (hot), with a vote of +1, 0 or -1 indicating a comfortable state.

The steady-state approach is encapsulated in ISO 7730:2005 [10] and ASHRAE-55 [11] and the adaptive approach in [9]. The indoor environment is considered acceptable when 80% of occupants feel comfortable, i.e. present thermal sensation vote in the range comfortable range is -1 to +1. The operative temperature (given by combining indoor air temperature, mean radiant temperature, and air velocity) rather than the air temperature is used to characterise the environment as it is known to better describe human sensation [12].

ISO 7730:2005 is normally applied to healthy populations that stay predominantly indoors, although designed primarily for the work environment, it can also be applied to some other environments, but not hospitals, as mentioned in Annex A of the standard.

Regarding the applicability of standards in hospitals, Lan and Lian (2016) stated that current thermal comfort approaches and standards are not suitable for people lying in bed, pointing out that Fanger's work was pioneered using college students in good health [13] and under steady state conditions. It is also known that patients and staff vary in their perceptions of the thermal indoor environment due to differing activity levels and clothing insulation [14]. People use a variety of ways to adapt to their thermal environment, but for patients, the options are limited. It is also known that the insulation provided by the patient's bedding (mattress, sleep wear and percentage of body covered) strongly influences the thermal comfort of patients, particularly those with lower mobility [15]. A study of three private Malaysian hospital wards [16] showed that the local guidelines for tropical regions such as *DOSH 2010* and *MS 1525-2014* could not be met in 54% and 73% of the measured thermal environment results, respectively. Furthermore, Del Ferraro et al. stated that the patient population is rarely described by the PMV model in their study of ten wards in an Italian hospital [17].

Many more thermal comfort studies have been completed in office and residential buildings [18], [19], [20] but also to temporary shelters, classrooms, hospitals, theatres and residences used in homecare [21], [22], [23], [24]. In such studies, researchers have generally combined the measurement of the indoor environments, with subjective responses (surveys) of individuals in those environments. Table 1 presents research studies into hospital thermal comfort. The climates were classified based on the five main groups of the Köppen Geiger climate zones map [25].

Table 1. Field studies in hospitals across a range of climates and the main findings.

Reference	**Köppen Climate/ Season**	**Size of trial and Main Findings** regarding thermal comfort approach/ applicability of Standards.
Pourshaghaghy and Omidvari (2012) [26]	BWh Summer/winter	84 patients, 39 staff, 32 visitors. PMV in Urgency, Radiology, Surgery, and Laboratory sections for both genders were not within an ISO 7730:2005 acceptable range.
Khodakarami and Knight (2008) [27]	BWh ---	14 patient rooms in 4 hospitals. Indoor thermal conditions were not in line with the thermal comfort conditions recommended by ASHRAE-55 2013, ISO 7730:2005, and CIBSE environmental design Guide A.
Hwang et al. (2007) [28]	Cfa Summer/winter	927 patients. TSV of patients indicated a comfortable environment by exceeding the Standard's 80% criterion, regardless of whether the physical conditions were in or out of the comfort zone.
Balaras, Dascalaki and Gaglia (2007) [29]	Csa ---	20 operation rooms in 10 hospitals. In most of the audited operation rooms the indoor conditions did not fit in with the ideal indoor conditions suggested by different global standards, controls and rules.
Hashiguchi et al. (2008) [30]	Csb Winter	36 patients, 45 staff. Air temperature in patient rooms was lower than that required by the local standards, (the difference was not critical).
Wang et al. (2012) [31]	Csc Summer	403 hospital staff. 255 out of 403 participants (64%) felt dissatisfied with the thermal comfort expressed by TSV, despite over 80% of field measurement data complying with the ASHRAE-55 comfort zone. The operative temperature ranged from 22.9°C to 26.3°C and the work revealed that the staff preferred an operative temperature range approximately 1°C lower than that required by ASHRAE-55 2013.
Verheyen et al. (2011) [32]	Csc Winter/spring	99 patients. Thermal comfort as predicted by measurement of physical parameters and via survey of patients were similar, and PMV could be used to anticipate thermal comfort for all wards except neurology.
Azizpour, Moghimi, Salleh, et al. (2013) [33]	Af Summer/autumn	188 staff and visitors. Neutral temperature was predicted from +0.75 point rather than 0.
Skoog, Fransson and Jagemar (2005) [14]	Dfd Summer/winter	35 patients, 40 staff. Patients and staff did not perceive the hospital environment in the same way in both summer and winter. Patients preferred a higher temperature than staff.
Af Equatorial, fully humid		**Csa** Warm temperate, steppe, hot summer

BWh	Arid, desert, hot arid	**Csb**	Warm temperate, steppe, warm summer
Dfd	Snow, fully humid, extremely continental	**Csc**	Warm temperate, steppe, cool summer
		Cfa	Warm temperate, fully humid, hot summer

With the exception of Verheyen et al., which was for a temperate location, the findings from Table 1 confirm that conventional thermal comfort approaches are not suited to hospital environments. (It is also worth noting that even the hospital staff could not achieve thermal comfort.) With the growing use of air conditioning in hot climates [34], [35], it is possible that many more of the population in such countries are exposed to a narrower band of temperatures than once might have been the case, which might in turn reduce their view of the range of temperatures they might consider comfortable once in hospital. Due to the paucity of relevant studies in hot climates, this work is focused on such a climate, and moreover, will, unlike previous work, examine the confounding factors behind the suggestion made by Table 1 that ASHRAE-55 and ISO 7730:2005 are unsuitable when discussing patient comfort.

1.2. Research objectives

Following previous research in this area, this paper does not intend to discuss the validity of thermal comfort theory in general, because it has been examined and applied to a variety of building types across a range of climates. Instead, this research aims to determine whether a state-of-the-art, fully air-conditioned hospital located in a hot environment meets patient expectations, and whether the predictive equation of thermal comfort is more accurate than occupant surveys. This is important, as thermal comfort standards include such equations, and dynamic building simulations make use of these equations when predicting thermal comfort to inform the design of their HVAC systems. This aim was achieved for the entire sample and all the sub-samples of patients according to the following objectives:

- To collate distributions of TSV and calculated PMV data to reveal thermal acceptability percentages.
- To compare the differences between TSV and PMV data for single occupant patient rooms.
- To predict the neutral (comfort) temperatures using linear regressions and the Griffith's method as an alternative method to regression analysis.

2. Materials and Methods

The work was completed by field study in Saudi Arabia during the summer of 2017 by recording indoor environmental variables (air temperature, mean radiant temperature, relative humidity, and air velocity) alongside clothing levels and metabolic rates in the short-term patients' rooms, as well as surveying patients' perceptions of thermal comfort.

2.1. Sampling methods

A power calculation based on the standard deviation (0.94) obtained from previous work [32],[17] was performed using G*Power [36]. This indicated that a sample size of 112 would be required in order to yield statistically significant results (95% confidence).

The study was undertaken in three phases in May, June, and July of 2017. The fasting month of Ramadan occurred from 27 May until 24 June in 2017, so its presence in the study period required an extended period of monitoring before, during, and after its observance. The periods before and after Ramadan required the use of validation procedures to detect perceived differences, if any, even if patients were prohibited from fasting due to their medical conditions.

The following protocol was repeated every day:

- Measurements made between 11:00–16:00, (to avoid Doctor's rounds and visitor periods).
- All measured patient rooms were in the medical and surgical wards.
- The indoor thermal environment was monitored, simultaneously with the surveys, which were limited to 10-15 minutes per patient as conducted by [14].

2.2. The hospital

The International Medical Centre (IMC) (Fig. 1) in Jeddah, Saudi Arabia was selected for three reasons;

- It won the Healing Environment Award in 2012 in the Middle East [37], and hence might be seen as representing a high quality setting.
- Jeddah is located in the western region of KSA, and is classified as BWh (Arid, desert, hot arid) based on the Köppen Geiger climate zones that meets the climatic focus of this research.
- The hospital has a uniform internal layout so that all inpatient wards face south and north, thereby reducing potential design aspects effects such as variety of layouts and views.

Fig. 1. International Medical Centre, Jeddah, Saudi Arabia (pictures by IMC Research Centre, reproduced with permission).

2.3. Population sample

Consent was given by the Research Centre at the IMC. The study focussed on surgical and medical wards on the fourth and fifth floors, respectively, selected due to these having the highest utilization rates and the largest number of rooms compared to all other hospital wards. The differences between the two wards were as follows:

- The IMC surgical ward typically admits inpatients who are undergoing or who have ongoing surgical interventions after being diagnosed by a specialist.
- The IMC medical ward accommodates inpatients, who have an illness or ailment that requires medical observation and nursing care but not necessarily surgical interventions. The medical ward also often deals with diseases associated with long-term conditions such as cardiac, respiratory, and infectious conditions.

Some patients who were pre/post operation on the day or who could not communicate were excluded. Table 2 & Fig. 2 summarises the patient profile, which represented more than 70% of all patients.

Table 2. Distribution of patients by age and gender.

Age group	18-24	25-34	35-44	45-54	55-64	65-74	>74	Total
Male	5	15	8	11	11	5	6	61
Female	6	7	19	7	12	6	2	59
Total	11	22	27	18	23	11	8	120

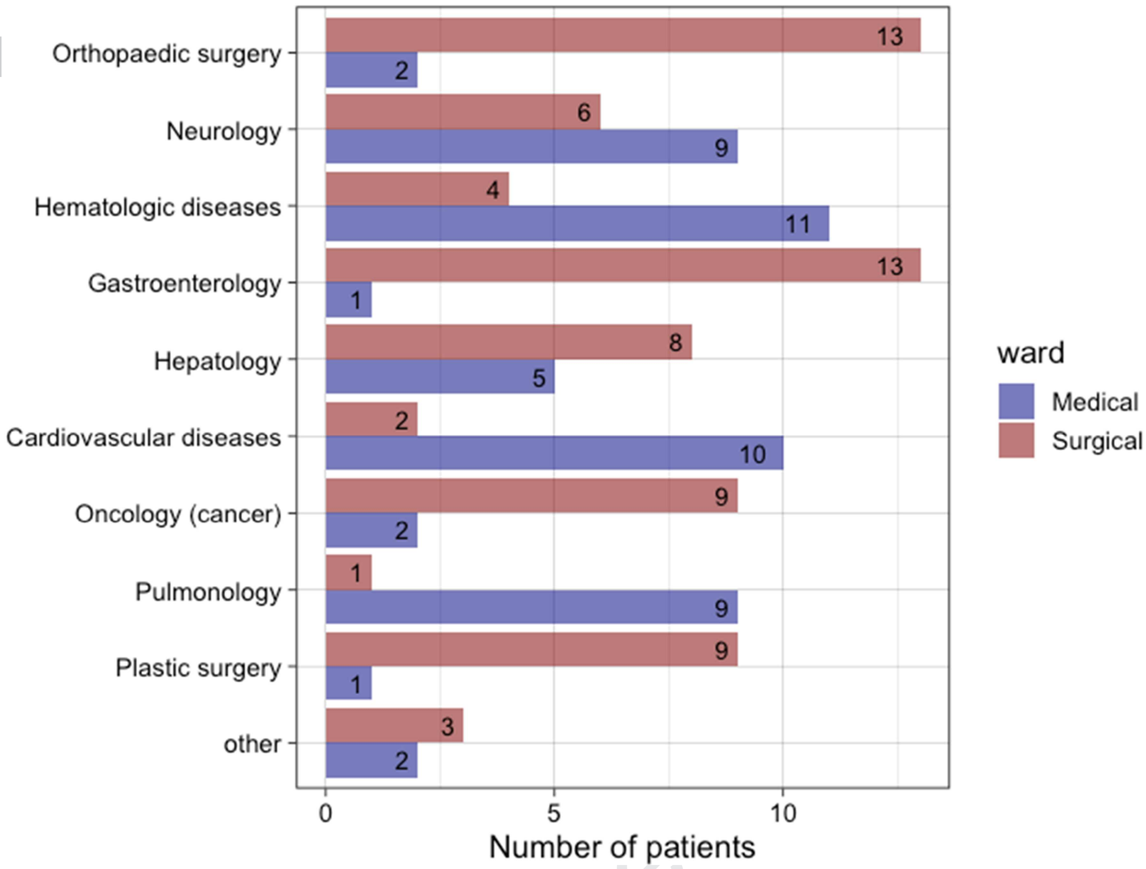

Fig. 2. Distribution of patients by illness and ward (order based on highest admission to each illness).

2.3.1. Subjective measurements

Before administering the surveys, the criteria were followed to select the sample patients were based on their ability to communicate/cooperate with researchers and the stability of their condition (e.g., no extreme pain, no ongoing medical procedures that require the patient to be alone, sleep or nap times/schedules, etc.). The selected medical and surgical wards were not considered specialist wards like those in other large hospitals that have specific wards for cardiology, oncology, etc. In line with Nicol, Humphreys, and Roaf (2012) the subjects were intimate with their ambient environment and the experiment did not conflict with the subjects' usual routine [38]. So, patients who were admitted on the same day were excluded due to the lack of acclimatisation with their ambient environments, which might cause a discrepancy in their judgment of the indoor environment.

The survey was originally developed and written in English and translated to Arabic and was distributed in both languages. All questions were initially closed questions to avoid undue stress to patients but later developed into more specific questions to gather the desired data, namely:

- Demographic profile of patients (i.e. gender and age) in seven bands (see Table 2), these bands are widely used in interdisciplinary surveys like [39], [40];
- Current health, gathered on a 5-point Likert scale (1 = very frail, 5 = vigorous) [32], Table 3;
- Thermal sensation votes, Table 4) (ASHRAE-55).

Table 3. Distribution of medical conditions

Sample	Health*				
	1	2	3	4	5
Overall	4	19	58	30	9
Male	1	8	31	17	4
Female	3	11	27	13	5
Surgical ward	1	10	31	16	4
Medical ward	3	9	27	14	5

*1 = very frail, 5 = vigorous.

Table 4. TSV phrasing and scoring.

TSV score	English phrasing	Arabic
+3	Hot	حار جداً
+2	warm	دافئ
+1	Slightly warm	دافئ قليلاً
0	Neutral	معتدل (حيادي)
-1	Slightly cool	بارد بعض الشيء
-2	Cool	بارد
-3	Cold	بارد جداً

2.4. Outdoor environment conditions

According to Department of Meteorology, King Abdul-Aziz University in Jeddah, the maximum temperature was 48.8˚C at the end of July and the minimum was 23.8˚C at the beginning of June in 2017. The highest relative humidity was recorded as 91% on the last day of June while the lowest was 9% at the beginning of July. This summer period was one of the hottest on record, Fig. 3 shows the monthly average temperature.

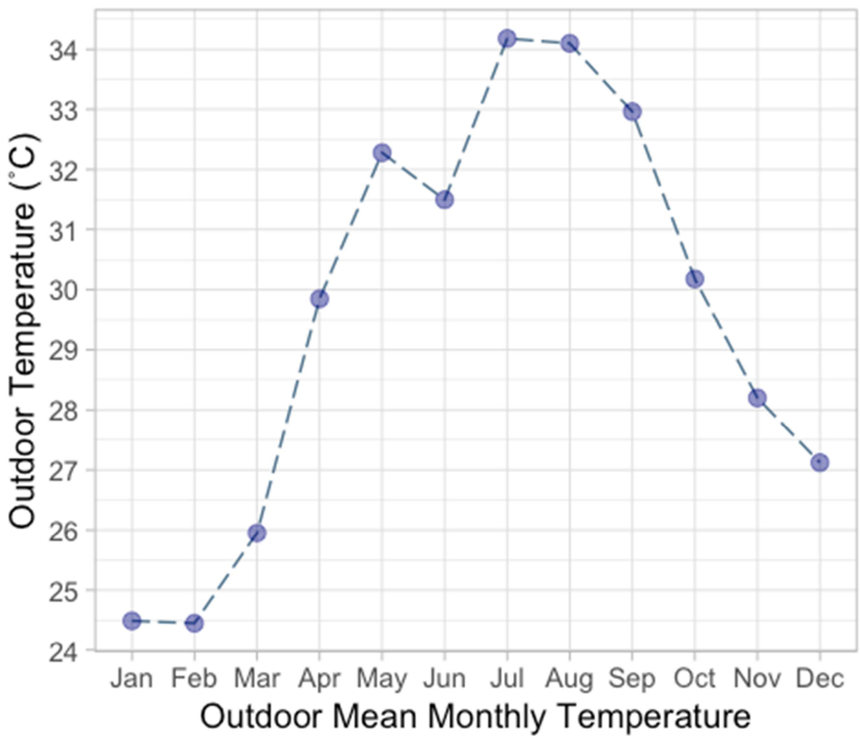

Fig. 3. The prevailing monthly mean daily outdoor temperature for Jeddah, Saudi Arabia in 2017 (Source: Department of Meteorology, King Abdul-Aziz University in Jeddah).

2.5. Measurements and calculation of indices

Indoor air temperature (T_a), mean radiant temperature (T_r), air velocity (V), and relative humidity (Rh), along with estimations of patients' metabolic rates and notes about clothing insulation (I_{cl}), were recorded [41]. Swema monitoring equipment [42] was used to record these environmental parameters, meeting the requirements of ISO 7726 [43] and ISO 7730:2005 (see Appendix A). The Swema sensors were configured to sample measurements at 0.1s intervals and record average values every 10 mins. The sensors were located at the foot of each patient's bed and arranged at bed height to maintain patient comfort while not interfering with the duties of medical staff (Fig. 4).

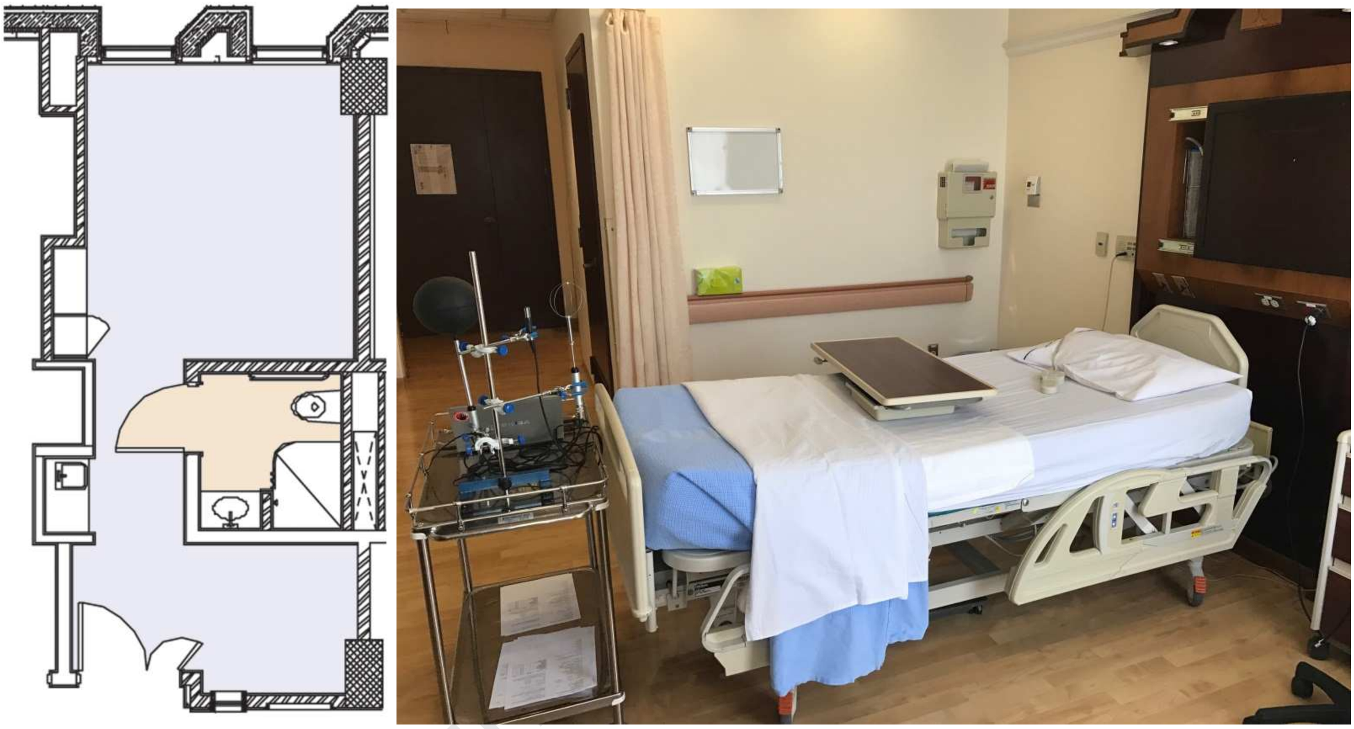

Fig. 4. Standard patient room (single occupancy) layout at IMC (left) and Swema equipment position in a vacant patient room at IMC hospital (right).

As the hospital was air-conditioned and well-controlled, the indoor temperature did not follow the outdoor climate. However, it varied substantially between the rooms due to the actuation of room thermostats by patients or their relatives. Table 5 and Fig. 5 summarise the measured parameters.

Different hospital spaces in the hospital environment require their own unique design norms and a specific approach to air distribution based on the space's function. This research considers single-occupancy inpatient rooms, with a minimum of two un-openable, double-glazed windows and moveable curtains. As such the rooms at IMC comply with the design norms suggested by the standards for the ventilation of healthcare facilities (ANSI/ASHRAE-170:2013) [44], which are as follows:

- The design temperature is 21–24°C, and the relative humidity is a maximum of 60%.
- The supply air outlet follows the Group A1 outlet type as classified in chapter 20 of the 2017 ASHRAE Handbook—Fundamentals [45].
- An outlet position must be situated where it cannot be accidentally unplugged.

Central HVAC system is used at the IMC to cool/heat the indoor environment and to maintain the acceptable ventilation requirements. All patient rooms were supplied by fresh air through ductwork that connected to an air handling unit (AUH), which is a large metal-box adjacent to the building. The AUH converts the outdoor air and circulates it through several processes before supplying a patient room [46]. Each patient room contained two linear, ceiling-mounted diffusers and two air-exhaust diffusers, one in the bathroom and the other near the door into the patient room (ceiling-mounted).

Table 5. Descriptive statistics of the environmental data. (Data shows average ± SD: standard deviation)

Indoor Variable	Overall			Gender		Surgical ward	Medical ward
	min.	mean	max.	M	F		
T_a (°C)	20.24	23.17 ± 1.07	25.48	23.15 ± 1.13	23.18 ± 1.02	22.93 ± 1.01	23.43 ± 1.08
T_r (°C)	20.95	23.40 ± 0.90	25.71	23.42 ± 0.90	23.39 ± 0.90	23.23 ± 0.81	23.59 ± 0.96
Rh (%)	41.51	48.31 ± 3.91	60.35	47.85 ± 3.51	48.78 ± 4.26	47.76 ± 3.53	48.90 ± 4.23
V_a (m/s)	0	0.04 ± 0.05	0.24	0.03	0.04	0.04	0.04

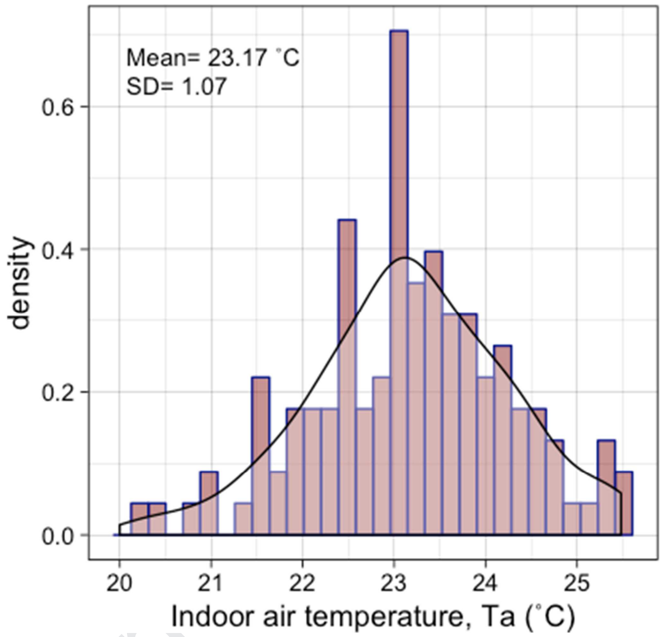

Fig. 5. Distribution of measured air temperatures, T_a. The curved line is the Kernel smoothing.

2.5.1. Metabolic rates and clothing insulation

Metabolic rates of patients were estimated according to ASHRAE-55 and ISO 8996:2004 [47] by observing patients for 10 min while measuring environmental parameters in each room. Two positions were found: sleeping (0.7 met), and reclining (0.8 met). Estimating the thermal insulation of clothing for patients and sleeping environments posed a few challenges as the clothing insulation (I_{cl}) ensembles worn are not documented in ASHRAE-55 and ISO 9920 [48]. Firstly, the insulating effect of bedding materials differed from those of chairs (where most occupants are reported in residential and office buildings comfort surveys). Moreover, pullover gowns worn as sleepwear by patients might be full- or half-length. The insulation provided by such ensembles of clothing was difficult to find in the literature. Lastly, the values of clothing insulation could not be calculated by using equation 11 in ISO 9920, because it does not consider the insulating effect of bedding materials [17].

To overcome those challenges, reference was made to Lin and Deng (2008), who measured total insulation values for bedding materials commonly used in subtropical environments by applying a selection of bedding, sleepwear, and mattresses to a prostrate thermal mannequin in an environmental chamber [15]. Their method has guided most recent research on sleeping environments [49], [50], [51], [52], [53], [54], [55], and [56], particularly in hospitals [32], [17], and [16]. Two combinations of garments (i.e. C1 and C2, below) were used in the study reported here, each of which included bedding, a conventional mattress, and sheets, along with a blanket and half- or full-slip sleepwear (Table 6). The percentage of bodily surface covered was recorded for each patient (Fig. 6).

Table 6. The total insulation values (in clo) based on percentage coverage of body adopted from [15].

Ensemble code	23%	48%	59%	67%	94%
C1[a]	1.57	1.82	2.08	2.18	2.56
C2[b]	1.38	1.43	1.76	1.80	2.40

a: blanket+ full-slip sleepwear, b: blanket+ half-slip sleepwear

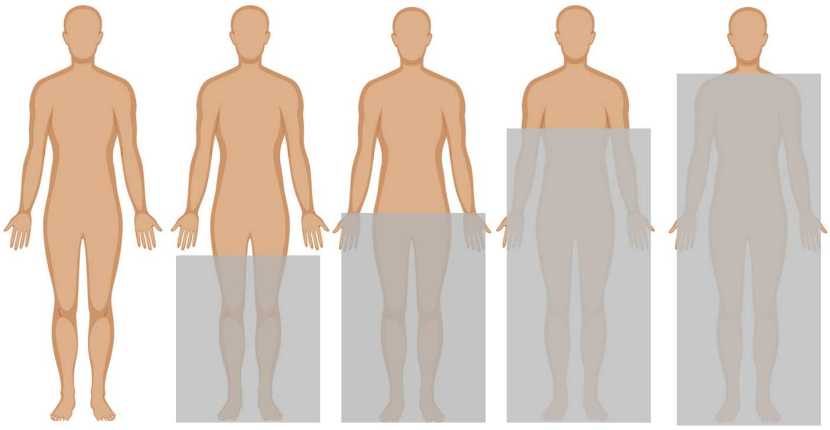

Fig. 6. Percentage coverage of body surface area by bedding and bed recorded in the experiment [57].

2.5.2. Calculated PMV

The PMV model was pioneered for moderate ranges of metabolic rates of 46-232 W/m^2 (0.8 - 4.0 met) ISO7730. However, Lin and Deng [58] showed that the model is still valid at a lower metabolic rate of 40 W/m^2 (0.7 met) when sleeping. During the study the garments (i.e. short- or long-sleeve pullover gown, plus percentage of bodily surface coverage by blankets or sheets, plus bedding system) were recorded and the PMV of each patient was calculated using a CBE Thermal Comfort Tool for ASHRAE-55 developed at the University of California, Berkeley [59].

2.5.3. Operative temperature (T_{op})

Calculating the operative temperature is one of four methods of determining acceptable thermal comfort in occupied spaces in ASHRAE-55, and involves combining air and radiant temperatures with air speed (Equation 1 in ISO 7726):

$$T_{op} = \frac{T_r + T_a\sqrt{10V}}{1 + \sqrt{10V}} \qquad (1)$$

T_{op} was calculated for all 120 records and checked for normality using a Shapiro-Wilk test [60] (Fig. 7).

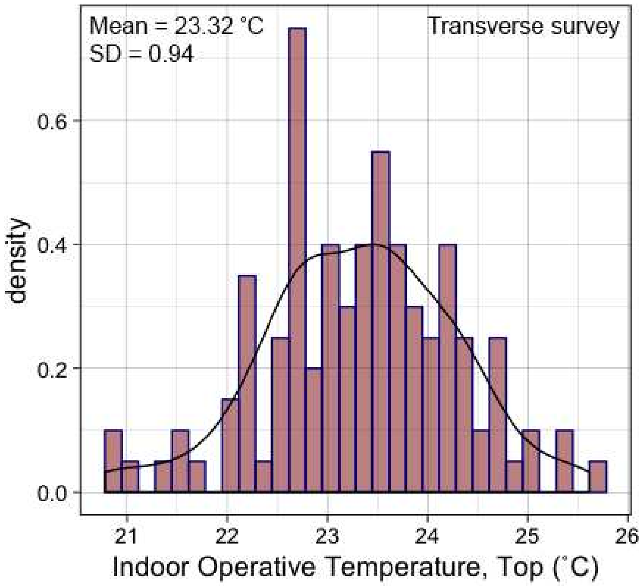

Fig. 7. Histogram showing the indoor operative temperature is approximately normally distributed. The curved line is the Kernel smoothing.

2.6. Statistical methods

The data was classified into sub-groups by gender, wards and severity of medical conditions, similar to Del Ferraro (2015) who evaluated the differences in gender and age in an Italian hospital [17], and another study by Azizpour et al. (2013) which assessed thermal comfort for non-patients in a large hospital [33].

3. Results and discussion

3.1. Distribution of data

Fig. 8 shows the distribution of TSVs from the surveys and the calculated PMVs. According to ISO 7730:2005, the comfortable range is -0.5 ≤ PMV ≤ +0.5, and according to ASHRAE-55, the comfortable range is -1 ≤ TSV ≤ +1. From Table 7, we see that the whole sample and sub-samples of the TSV for patients did not fall into the acceptable zone and varied between 55-74%.

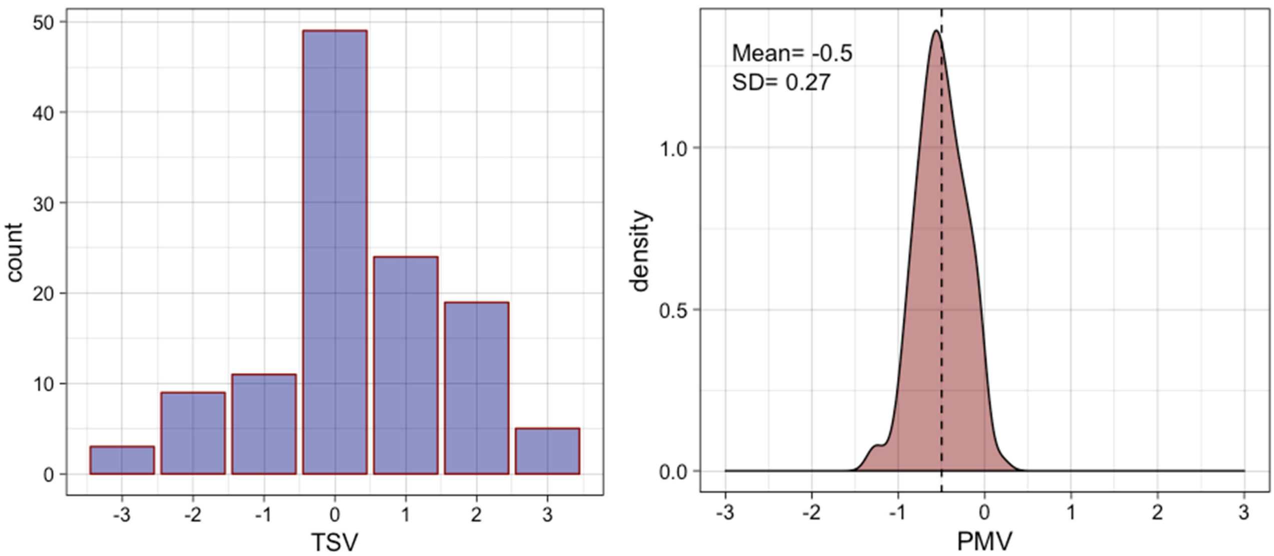

Fig. 8. TSV and PMV distribution overall. The mean PMV is marked.

Most rooms gave a PMV ≤ -0.5, i.e. slightly cool, and cool. It was not surprising that the PMV model (-0.5) was lower than the actual thermal perception of patients (as represented by their TSV; mean = 0.32) due to their reduced clothing layers and low activity when patients were hospitalised, as this also corresponded to other sub-categories as seen in Table 7. This was attributed to the fact that patients rarely had opportunities to adjust their environment since they could not open their windows or wear what they wanted to, this reduced the priority of physical adaptation because of the patients' medical condition, as suggested by [30]. This (PMV ≤ -0.5) was similar to the investigation of objective and subjective measurements in a Belgian hospital [32], and Del Ferraro et al., (2015) highlighted differences in age and gender in an Italian hospital [17] while overestimation of the PMV was reported by Hwang *et al.*, (2007) for studying patient thermal comfort requirements in Taiwan [28].

Table 7. Thermal acceptability percentage for both subjective and objective measurements.

Thermal accessibility	Overall	Gender		Ward		Health				
		M	F	Surgical	Medical	1	2	3	4	5
-1≤ TSV ≤ +1	70%	73%	69%	74%	65%	-[a]	57%	74%	70%	55%
-0.5 ≤ PMV ≤ +0.5	50%	52%	50%	35%	50%	-[b]	42%	44%	50%	44%

[a,b]: sample size too low.

3.2. The relationship between TSV and PMV

A t-test between the PMV and TSV were computed among the whole sample and subsamples. This reported statistically significant differences (Table 8 & Fig. 9). However, in the case of the PMV, it revealed that the means of the PMVs between the male and female was not noticeable while the difference between surgical and medical wards was statistically significant (t= -2.207, p-value < 0.02). This was interesting because patients undergoing chronic treatment and medication in the medical ward felt more comfortable, (even though they had lower activity levels), than those in the surgical ward, who were subject to less-adverse conditions and felt, perhaps, similar to healthy occupants.

Table 8. The results of the two-sample t-test for TSV and PMV for the overall and sub-samples.

Subject	TSV (mean)	PMV (mean)	t^*	Confidence bands 99%		p-value
Overall	0.32	-0.5	6.780	0.51	1.15	Significant ($P < 0.000$)
Male	0.09	-0.52	3.729	0.18	1.06	Significant ($P < 0.000$)
Female	0.55	-0.48	5.942	0.57	1.51	Significant ($P < 0.000$)
Surgical ward	0.16	-0.56	4.180	0.26	1.19	Significant ($P < 0.000$)
Medical ward	0.5	-0.44	5.520	0.48	1.39	Significant ($P < 0.000$)

**The t-value measures the size of the difference relative to the variation in the data.*

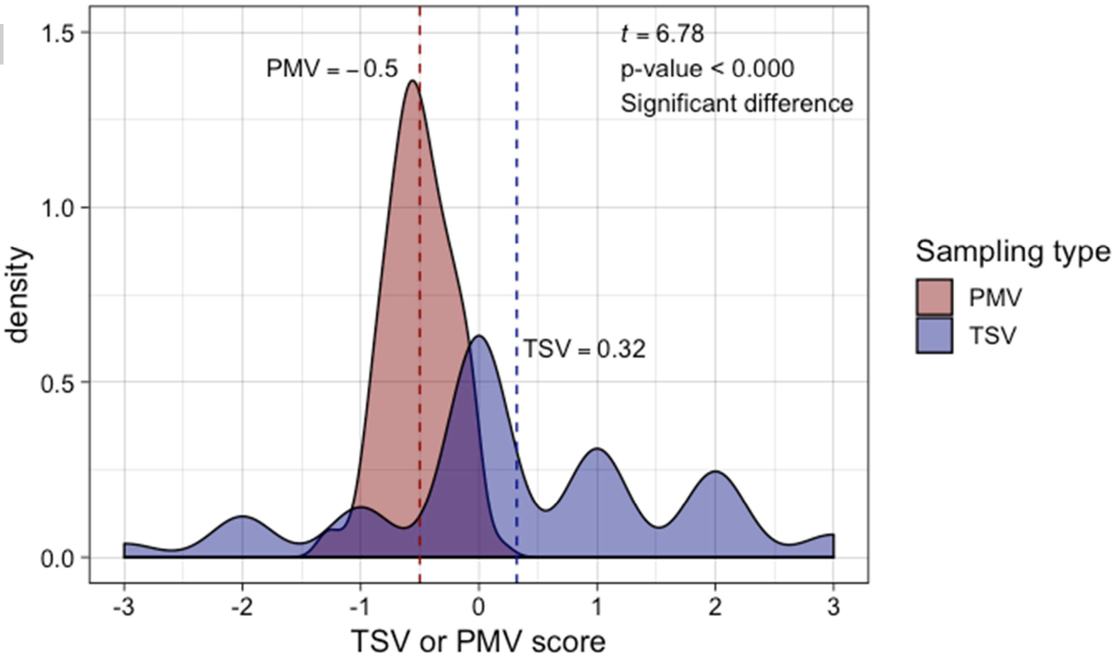

Fig. 9. Comparison between the TSV and the PMV values among patients.

The Male TSV mean (0.09) was close to the neutral point (i.e. zero) while the female mean (0.55) shifted towards slightly being too warm (0.55), hence the male group was more acclimatised to the hotter indoor environment conditions. Another important indicator for patients during hospitalisation was their medical condition at the moment of undertaking the survey and its impact on thermal levels. Patients were able to rank the severity of their health on scale of 1 to 5 (1= frail, 5= vigorous). No effect of these medical conditions was detected after computing the One-way ANOVA test due to insufficient power to run the analysis (the confidence interval less than 95%). Again, the PMV index (Table 8) was lower than the patients' perception of the thermal environment for overall samples. A boxplot comparing the PMV and the TSV among all sub-samples is presented in Fig. 10, showing very narrow ranges of PMVs compared to TSVs, indicating how the PMV index does not take into account complex human interactions.

By contrast, the only study reported no significant difference between the TSV and the PMV for all wards except the neurology ward was in a Belgian hospital [32]. This study believed this similarity was due to the following:

- Patients expected a lower comfort temperature, similar to that expected by healthy occupants.
- Clothing insulation, bedding system effects, and activity levels might be systematically underrated, causing a reduction in PMV values.
- High thermal acceptability rates in TSV could be explained by the fact that patients responded in the 'neutral category' where surveys were answered (with no specific vote on the focus of their attention at the time of asking). This was in line with the previous work [61].

This similarity between the TSV and PMV in [32] contradicts the majority of similar field studies conducted in different climatic and geographical zones. In tropical climates, the TSV was higher than the calculated PMV of patients' perception of cold [62], indicating that patients demanded a colder temperature in such a climate. In a Mediterranean climate, the difference between the TSV and PMV was discordant, with TSV remaining on the warm side while PMV moved toward both the warm and cool sides [17]. On the other hand, the PMV model overrated the TSV in a study in a hot, humid climate [28], concluding that a warmer perception is preferred over neutrality for patients in that climate.

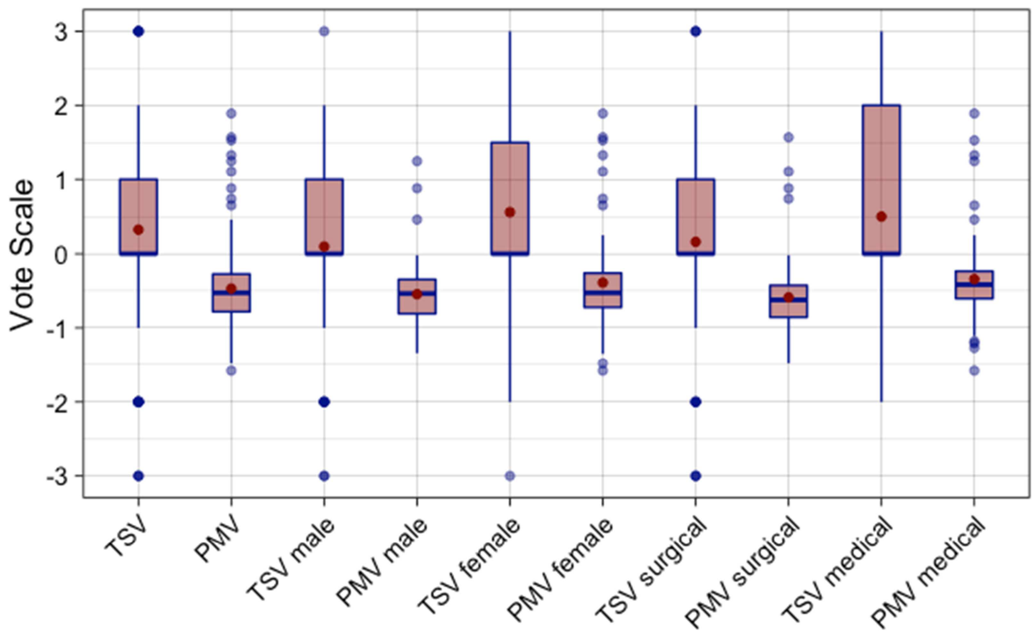

Fig. 10. Comparison of PMV and TSV among all sub-samples. Red dots indicate the mean, the box shows the first and third quartiles with a horizontal line at the median, blue dots located outside the whiskers show data more than 1.5 times the interquartile range

3.3. Neutral temperature (T_n)

The neutral temperature, i.e. the temperature where TSV or PMV equals zero, was found by linear regression. TSV & PMV were pooled with T_{op} as a predictor variable (the regression was derived from 0.5 T_{op} bins rather than individual votes). In most cases the R^2 generated from the TSVs was too small for a liner relationship to be considered valid and this was confirmed by the data (Fig. 11). Hence it is clear that the concept of a neutral temperature derived from the TSVs for this group of people is invalid (Table 9). As the PMV in this work has been calculated from the measured physical parameters, one of which is the temperature, it is unsurprising that the fit to the data is better (Fig. 11). This allowed the neutral temperature to be identified (Table 10).

Table 9. Linear regressions for TSV, PMV and T_{op} overall and with sub-group.

		Overall	Gender		Ward		Medical condition				
			M	F	Surgical	Medical	1	2	3	4	5
R^2	TSV	0.463	0.127	0.065	0.137	0.021	-[a]	0.484	0.095	0.004	0.179
	PMV	0.938	0.968	0.929	0.971	0.761	-[b]	0.620	0.428	0.697	0.528

[a,b]: p-value > 0.05.

The observed TSV R^2 of 0.463 is though higher than some other studies in hospitals: 0.047 by [16], 0.131 by [62] but mismatched totally with an Iranian hospital of (0.965) that focused only on staff [63], undertaken in the same climate zone (BWh) as our research. This all suggests that the idea of controlling hospital room conditions centrally and based on a single neutral temperature is unlikely to be valid.

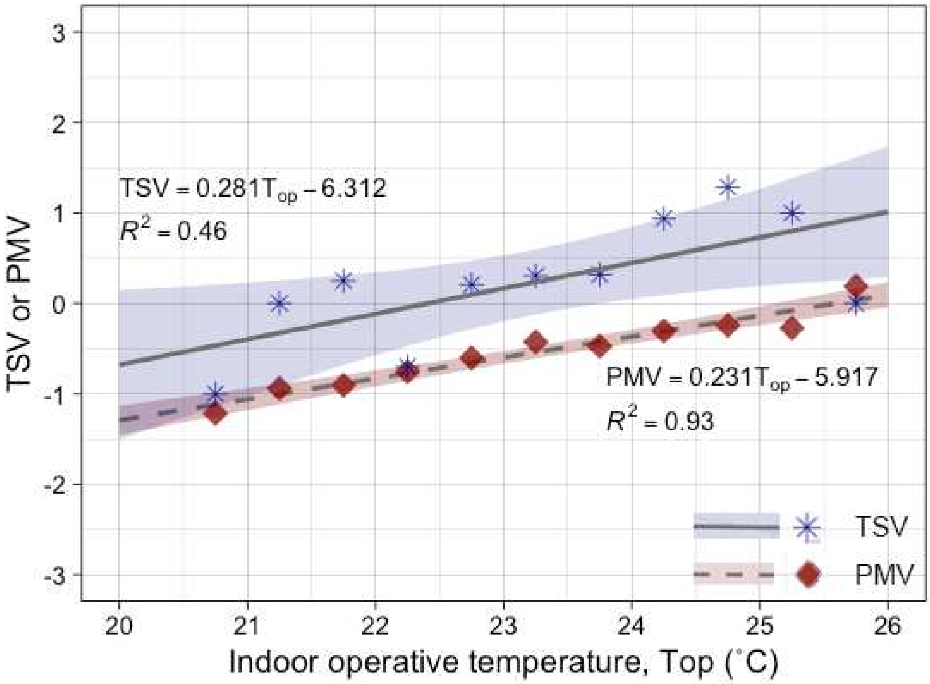

Fig. 11. PMV and TSV (95% confidence bands). Note: the data has been placed into bins, hence each point presents many data points.

Table 10. Linear regressions for PMV including sub-samples (Neutral temperature was calculated based on 95% confidence interval).

			α(/°C)	b^*	p-value	R^2		T_n ± SE(°C)
PMV	Overall		0.2312	-5.9177	0.000	0.938	Significant	25.59 ± 0.45
	Male		0.2529	-6.3999	0.000	0.968	Significant	25.30 ± 0.46
	Female		0.1637	-4.3524	0.000	0.929	Significant	26.58 ± 0.75
	Surgical ward		0.2921	-7.2345	0.000	0.971	Significant	24.76 ± 0.54
	Medical ward		0.2720	-6.9529	0.000	0.761	Significant	25.56 ± 2.17
	Health	1	-	-	0.9	-	Not significant	-
		2	0.2004	-5.1462	0.000	0.620	Significant	25.67 ± 0.88
		3	0.2622	-6.6004	0.000	0.983	Significant	25.17 ± 0.50
		4	0.3274	-8.0446	0.02	0.998	Significant	24.57 ± 0.33
		5	0.1579	-4.1883	0.02	0.528	Significant	26.52 ± 1.32

3.3.1. Griffith's method

An alternative way of predicting T_n from TSV is Griffith's method [64] which is a more appropriate approach in the case of low sample sizes and small ranges of temperature [65],[66] and in the case of linear regression did not give a significant correlation with T_{op} :

$$T_n = T_{op} + (0 - TSV)/\alpha \qquad (2)$$

where α is Griffiths' constant. In the literature, researchers have used 0.25, 0.33 and 0.5/K as this coefficient but [67] estimated it to be above 0.40. Fieldwork undertaken in similar climates selected a coefficient value of 0.5 for a variety of buildings such as in offices in Qatar [68], in universities [69], [70], in hospitals [16]. Taking this value for α gives Fig. 12, and the T_n's given in Table 11.

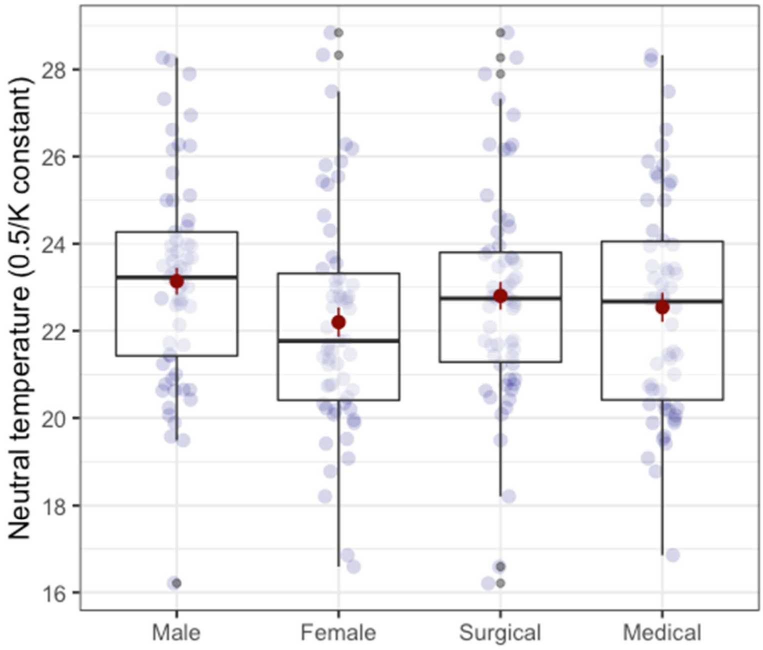

Fig. 12. Neutral temperature among sub-samples based on Griffiths' method. Red dot indicates the mean, the box indicates the first and third quartiles with a horizontal line at the median, values located outside the whiskers show data more than 1.5 times the interquartile range

Table 11. Neutral temperature (T_n) from TSV by Griffith's method.

	Overall	Gender		Ward		Medical condition				
		M	F	Surgical	Medical	1	2	3	4	5
T_n (°C)	22.67	23.13	22.19	22.8	22.53	23.02	21.95	22.41	23.22	23.85

Unexpectedly, a t-test reported a statistically significant difference between males and females in the means of T_n calculated based on Griffiths' method (t= 2.057, p-value= 0.04) while the difference between surgical and medical wards was negligible. Also, an ANOVA test showed that no significant differences were found among the medical conditions 5-points scale in their T_n.

3.4. Multivariate analysis

Due to many conflicting factors prevalent during hospitalisation of patients, all continuous independent variables (IV) were examined simultaneously with the TSV as the dependent variable (DV) to reveal how these factors could affect patients. Multiple linear regression has been applied widely in thermal comfort research [71] particularly using the steady-state approach as it helps to determine the correlation of two or more IVs simultaneously. Following Sharma and Ali (1986), multiple linear regression analysis of the data was computed to derive an equation that showed the perturbation required of IV for a unit rise in the TSV [72]. An inter-correlation matrix is presented to determine the relationships between IV's (Fig. 13) and to check the required assumptions for this model with the most important requirement being the multicollinearity that is a statistical issue where two or more continuous independent variables must be not too closely correlated (r > 0.8) by applying the '*Pearson'* correlation test. As a consequence, this model will yield redundant equations and unreliable model results of the TSV with selected IV's. All correlations were found to be weak (Fig. 13) except those between the air and radiant temperature with PMV, which given these are the driving terms in the equation used for PMV, is unsurprising.

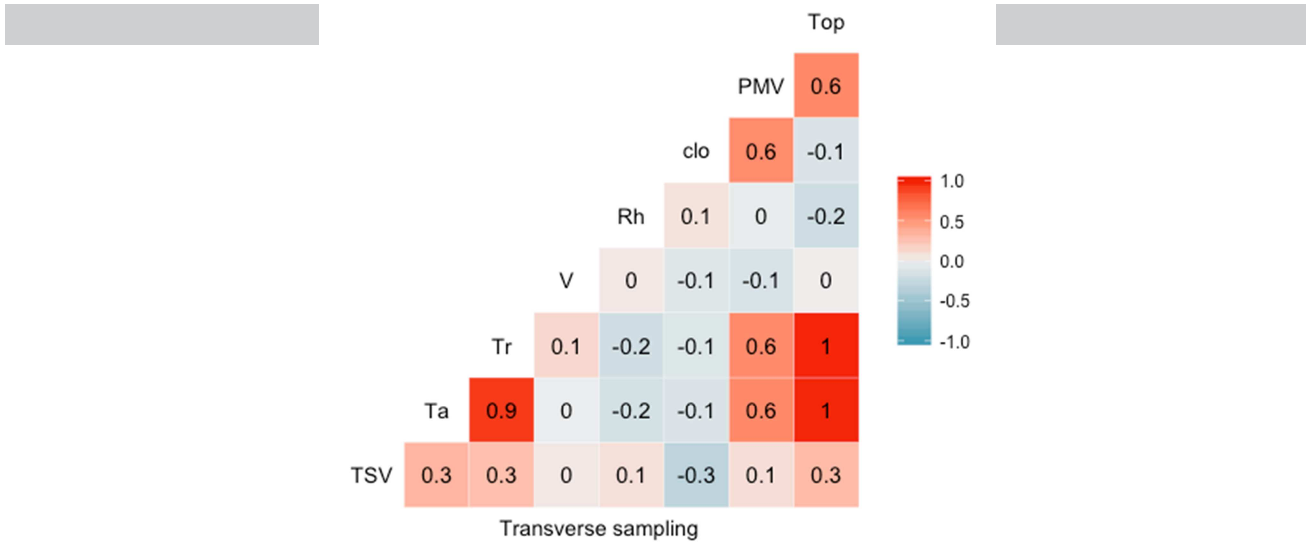

Fig. 13. Intercorrelation matrix of indoor environmental variables showing the Pearson correlation coefficient.

3.5. Discussion

Over the past two decades, thermal comfort models have been used to evaluate the thermal environment in hospitals despite the fact that such models were pioneered for healthy occupants. Research using these models in hospitals was commonly based on either comparing the TSV and the PMV of patients to those of staff, or by predicting the T_n from the TSV and the PMV for both hospital users. The majority attempted to reveal the distinctions between patients and staff and how they perceived the thermal environment given their existing medical conditions. It is evident that the thermal preferences of patients and non-patients are indeed easily distinguishable in the same hospital environment [14].

In our work, statistically significant differences were identified between the TSV and PMV over the whole sample of patients and sub-samples by gender and wards. Finding the neutral temperature from TSV failed due to a low R^2, so T_n was computed by Griffith's method, giving 22.67 °C. The predicted neutral temperatures from previous hospital research were (in hot and humid climates): 25.2°C in [62], 26.4°C in [73], 23.2°C in [28], and 22.4°C in a cold climate [14].

The likelihood of the external climate affecting patients' thermal comfort and the indoor environment of hospitals is not obvious due to the disparity between findings from different climates, as mentioned in section 3.2. Nicol and Roaf stated that the global standards for indoor human occupancy, such as ISO7730 and ASHRAE-55, did not consider the impact of climate due to garments, and activity levels cannot be accurately determined, as they are based on estimations not calculations. This means that the standards suggest a specific temperature to be applied despite climate or season, even though there is an obvious distinction between summer and winter [74]. Hwang et al. confirmed that 75% of patients in a hot, humid climate preferred higher humidity levels than those suggested by ASHRAE-55 [28].

Regarding health effects, patients' physical strength was examined via 7-point-scale thermal sensation in [28], which showed that vigorous patients felt slightly warmer than neutral (0.13), while frail patients were close to the neutral point (-0.05), indicating that physical strength had a statistically significant impact on patient thermal sensation votes. Khalid et al. also pointed out that overall comfort, thermal preferences and air quality were substantially affected by a patient's medical condition [16]. Confounding factors, such as the nature and acuity of patient ailments during hospitalisation as well as environmental control parameters from the building side, need to be fully specified.

The severity of certain medical conditions requires knowledge of medications or interventions that influence patients' internal thermoregulatory systems. In [32], patients hospitalised in the neurology ward showed a disparity in their perceptions of the thermal environment compared to those in the oncology, gastroenterology, maternity, or abdominal surgery wards. The study stated that surgery or injury of the brain and nervous system had a high impact on thermophysiology and thermoregulation. Addressing these related points will promote a better understanding of the PMV model and enable its modification to be more representative of patient thermal comfort.

6. Conclusions

This research was aimed at discovering: (a) the degree of diversity in the indoor environment that patients desire; (b) whether the calculated PMV and the resultant neutral temperature gives a reasonable reflection of these desires.

120 measurements of indoor air temperature, mean radiant temperature, air velocity, and relative humidity, along with estimations of patients' metabolic rates and notes about clothing insulation, were recorded during summer in a modern air-condition hospital in Jeddah. These were used to give the same number of predictions of PMV, via Fanger's method and to identify the neutral temperature via regression (25.6°C, Std. error ± 0.45). Collating the data by type of ward, gender and severity of medical conditions, gives sub-group neutral temperatures of (male: 25.3°C, female: 26.6°C, surgical ward: 24.8°C, and medical ward: 25.6°C).

At the same time as the physical measurements, 120 TSVs were obtained for the 120 of patients in the same rooms as the physical measurements using a survey in English and Arabic. The TSVs were found to be extremely scattered, and attempts to use regression to find the relationship between the operative temperature and the TSV from this data failed, and hence no neutral temperature could be identified. This was true of the data in general, and of the sub-groups. This strongly suggests that patients in hospitals are facing conditions that are far from ideal, and as previous work [32] has shown that a lack of thermal comfort has an effect on patients thermos-physiology, blood flow, regulatory response, and thermal perception, this might have health-related repercussions. Indoor environments are normally considered thermally acceptable when 80% or more of occupant TSVs lie between -1 and +1, however we found values as low as 55%, reinforcing the conclusion that the situation is far from ideal.

The diversity in thermal requirements was emphasized by the use of Griffith's method to identify the range of neutral temperatures expressed by the patients, with the result being 16.2°C to 28.8°C (mean = 22.7 °C; SD = 2.51).

In order to provide a comfortable thermal environment for patients, which basically determines their experience during hospitalisation, future work must classify patients by illness and possibly mention the effects of certain medications on patient heat production (absolute metabolic rates rather than estimations). One limitation of our work was that it was difficult to cover many ailments with a variety of acuity, because IMC is a private general hospital with slightly lower admissions than public or state hospitals. The average stay was five days in normal cases and two to three weeks for critical cases.

Although it is unknown what lies behind this diversity, likely candidates would be changes to metabolic output due to medical conditions, and the lack of ability to easily make changes to clothing and bedding—the latter two suggesting part of the problem might be improved by tailored hospital practices targeted to individual patients.

Acknowledgements and Data Statement

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Appendix A:

Sensor specifications.

Sensor	Parameter	Accuracy	Range
Swema 03	Air velocity	±0.03 m/s at 23°C	0.05…1.0 m/s
	Temperature	±0.3°C	At 23°C
		± 0.5°C	10…40°C
Swema 05	Globe temperature	±0.1°C	0…50°C
HC2-5	Air humidity	± 1%RH at 23°C	0…100% RH
	Temperature	± 0.1°C	-40…+60°C

References

[1] K. Dijkstra, M. Pieterse, and A. Pruyn, “Physical environmental stimuli that turn healthcare facilities into healing environments through psychologically mediated effects: Systematic review,” *J. Adv. Nurs.*, vol. 56, no. 2, pp. 166–181, 2006.

[2] R. Codinhoto, P. Tzortzopoulos, M. Kagioglou, G. Aouad, and R. Cooper, “The impacts of the built environment on health outcomes,” *J. Public Ment. Heal. Iss An Int. J. Iss J. Facil. Manag.*, vol. 27, no. 3, pp. 138–151, 2009.

[3] J. Khodakarami and N. Nasrollahi, “Thermal comfort in hospitals - A literature review,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, pp. 4071–4077, 2012.

[4] H. Salonen *et al.*, “The effects of the thermal environment on occupants’ responses in health care facilities: A literature review,” in *9th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings (IAQVEC2016), 23-26 October2016, Songdo, Incheon, Republic of Korea*, 2016.

[5] R. Kameel and E. Khalil, “Thermal comfort VS air quality in air-conditioned healthcare applications,” in *36th AIAA thermophysics conference*, 2003, p. 4199.

[6] I. D. A. Johnston and A. R. Hunter, *The Design and Utilization of Operating Theatres: From a Working Party on Operating Theatre Design in Relation to Surgical Training and a Symposium on Operating Theatre Utilization Organized by the Royal College of Surgeons of England and the Faculty of Anaesthetists*. Edward Arnold, 1984.

[7] P. O. Fanger, “Thermal comfort. Analysis and applications in environmental engineering.,” *Therm. Comf. Anal. Appl. Environ. Eng.*, 1970.

[8] Y. Al Horr, M. Arif, A. Kaushik, A. Mazroei, M. Katafygiotou, and E. Elsarrag, “Occupant productivity and office indoor environment quality: A review of the literature,” *Build. Environ.*, vol. 105, pp. 369–389, 2016.

[9] J. F. Nicol and M. A. Humphreys, “Thermal comfort as part of a self-regulating system,” 1973.

[10] ISO, “ISO 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria,” *Management*, vol. 3, pp. 605–615, 2005.

[11] A. Standard, “Standard 55-2013,” *Therm. Environ. Cond. Hum. Occup.*, 2013.

[12] K. W. H. Mui and W. T. D. Chan, “Adaptive comfort temperature model of air-conditioned building in Hong Kong,” *Build. Environ.*, vol. 38, no. 6, pp. 837–852, 2003.

[13] L. Lan and Z. Lian, “Ten questions concerning thermal environment and sleep quality,” *Build. Environ.*, vol. 99, pp. 252–259, 2016.

[14] J. Skoog, N. Fransson, and L. Jagemar, “Thermal environment in Swedish hospitals: Summer and winter measurements,” *Energy Build.*, vol. 37, no. 8, pp. 872–877, 2005.

[15] Z. Lin and S. Deng, “A study on the thermal comfort in sleeping environments in the subtropics-Measuring the total insulation values for the bedding systems commonly used in the subtropics,” *Build. Environ.*, vol. 43, pp. 905–916, 2008.

[16] W. Khalid, S. A. Zaki, H. B. Rijal, and F. Yakub, “Investigation of comfort temperature and thermal

adaptation for patients and visitors in Malaysian hospitals," *Energy Build.*, vol. 183, pp. 484–499, 2018.

[17] S. Del Ferraro, S. Iavicoli, S. Russo, and V. Molinaro, "A field study on thermal comfort in an Italian hospital considering differences in gender and age," *Appl. Ergon.*, vol. 50, pp. 177–184, 2015.

[18] M. Indraganti, "Thermal comfort in naturally ventilated apartments in summer: Findings from a field study in Hyderabad, India," *Appl. Energy*, vol. 87, pp. 866–883, 2009.

[19] R. Forgiarini Rupp and E. Ghisi, "Predicting thermal comfort in office buildings in a Brazilian temperate and humid climate," *Energy Build.*, vol. 144, pp. 152–166, 2017.

[20] F. Nicol, G. N. Jamy, O. Sykes, M. Humphreys, S. Roaf, and M. Hancock, "A survey of thermal comfort in Pakistan toward new indoor temperature standards," *Final Rep. to Overseas Dev. Adm. Publ. by Oxford Brookes Univ. Sch. Archit. UK*, 1994.

[21] R. M. Smith and a Rae, "Thermal comfort of patients in hospital ward areas.," *J. Hyg. (Lond).*, vol. 78, no. 1, pp. 17–26, 1977.

[22] M. A. Nico, S. Liuzzi, and P. Stefanizzi, "Evaluation of thermal comfort in university classrooms through objective approach and subjective preference analysis," *Appl. Ergon.*, vol. 48, pp. 111–120, 2015.

[23] D. Albadra, M. Vellei, D. Coley, and J. Hart, "Thermal comfort in desert refugee camps: An interdisciplinary approach," *Build. Environ.*, vol. 124, pp. 460–477, 2017.

[24] P. Ricciardi, A. Ziletti, and C. Buratti, "Evaluation of thermal comfort in an historical Italian opera theatre by the calculation of the neutral comfort temperature," *Build. Environ.*, vol. 102, pp. 116–127, 2016.

[25] M. Kottek, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, "World map of the Köppen-Geiger climate classification updated," *Meteorol. Zeitschrift*, vol. 15, no. 3, pp. 259–263, 2006.

[26] A. Pourshaghaghy and M. Omidvari, "Examination of thermal comfort in a hospital using PMV-PPD model," *Appl. Ergon.*, vol. 43, no. 6, pp. 1089–1095, 2012.

[27] J. Khodakarami and I. Knight, "Measured Thermal Comfort Conditions in Iranian Hospitals for Patients and Staff," *HVAC&R Res.*, 2008.

[28] R. L. Hwang, T. P. Lin, M. J. Cheng, and J. H. Chien, "Patient thermal comfort requirement for hospital environments in Taiwan," *Build. Environ.*, vol. 42, no. 8, pp. 2980–2987, 2007.

[29] C. A. Balaras, E. Dascalaki, and A. Gaglia, "HVAC and indoor thermal conditions in hospital operating rooms," *Energy Build.*, vol. 39, no. 4, pp. 454–470, 2007.

[30] N. Hashiguchi, M. Hirakawa, Y. Tochihara, Y. Kaji, and C. Karaki, "Effects of setting up of humidifiers on thermal conditions and subjective responses of patients and staff in a hospital during winter," *Appl. Ergon.*, vol. 39, no. 2, pp. 158–165, 2008.

[31] F. Wang, M. Lee, T. Cheng, and Y. Law, "Field evaluation of thermal comfort and indoor environment quality for a hospital in a hot and humid climate," *HVAC&R Res.*, vol. 18, no. 4, pp. 671–680, 2012.

[32] J. Verheyen, N. Theys, L. Allonsius, and F. Descamps, "Thermal comfort of patients: Objective and subjective measurements in patient rooms of a Belgian healthcare facility," *Build. Environ.*, vol. 46, no. 5, pp. 1195–1204, 2011.

[33] F. Azizpour, S. Moghimi, E. Salleh, S. Mat, C. H. Lim, and K. Sopian, "Thermal comfort assessment of large-scale hospitals in tropical climates: A case study of University Kebangsaan Malaysia Medical Centre (UKMMC)," *Energy Build.*, vol. 64, pp. 317–322, 2013.

[34] F. Alrashed and M. Asif, "Analysis of critical climate related factors for the application of zero-energy homes in Saudi Arabia," *Renew. Sustain. Energy Rev.*, vol. 41, pp. 1395–1403, 2015.

[35] H. Radhi, "Evaluating the potential impact of global warming on the UAE residential buildings – A contribution to reduce the CO 2 emissions," *Build. Environ.*, vol. 44, no. 12, pp. 2451–2462, 2009.

[36] F. Faul, E. Erdfelder, A.-G. Lang, and A. Buchner, "G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences," *Behav. Res. Methods*, vol. 39, no. 2, pp. 175–191, 2007.

[37] "International Medical Center," 2006. [Online]. Available: http://www.imc.med.sa/en/about-imc. [Accessed: 31-Aug-2017].

[38] F. Nicol, M. A. Humphreys, and S. Roaf, *Adaptive thermal comfort : principles and practice*. Abingdon: Abingdon : Routledge, 2012.

[39] T. Puoane *et al.*, “Obesity in South Africa: the South African demographic and health survey,” *Obes Res*, vol. 10, no. 10, pp. 1038–48, 2002.

[40] H. Tohid *et al.*, “Perceptions and attitudes to clinical research participation in Qatar,” *Contemp. Clin. Trials Commun.*, vol. 8, no. June, pp. 241–247, 2017.

[41] B. Alotaibi, “Dataset for ‘Evaluating the suitability of standard thermal comfort approaches for hospital patients in air-conditioned environments in hot climates.’” University of Bath, 2019.

[42] “Thermal environment Swema.com,” 2016. [Online]. Available: http://www.swema.com/instrument.php?p=Thermal environment&k=Swema.com. [Accessed: 01-Sep-2017].

[43] E. N. ISO, “7726,” *Ergon. Therm. Environ. Meas. Phys. Quant. (ISO 7726 1998)*, 1998.

[44] A. ASHRAE, “Standard 170-2013. Ventilation of Health Care Facilities,” *Am. Soc. Heating, Refrig. Air-Conditioning Eng. Inc, Atlanta*, 2013.

[45] A. Handbook, “Fundamentals, ASHRAE–American Society of Heating,” *Vent. Air-Conditioning Eng.*, 2017.

[46] S. Seyam, “Types of HVAC Systems,” in *HVAC System*, IntechOpen, 2018, pp. 49–66.

[47] B. ISO, “8996: 2004 Ergonomics of the thermal environment–Determination of metabolic rate,” *BSI, London*, 2004.

[48] ISO-9920, “Ergonomics of the thermal environment – estimation of the thermal insulation and evaporative resistance of a clothing ensemble,” 2006.

[49] P. Dongmei, C. Mingyin, D. Shiming, and Q. Minglu, “A four-node thermoregulation model for predicting the thermal physiological responses of a sleeping person,” *Build. Environ.*, vol. 52, pp. 88–97, 2012.

[50] C. Sun, Z. Lian, L. Lan, and H. Zhang, “Investigation on temperature range for thermal comfort in nonuniform environment,” *HVAC R Res.*, vol. 19, no. 2, pp. 103–112, 2013.

[51] L. Lan, L. Pan, Z. Lian, H. Huang, and Y. Lin, “Experimental study on thermal comfort of sleeping people at different air temperatures,” *Build. Environ.*, vol. 73, pp. 24–31, 2014.

[52] Y. Wang, Y. Liu, C. Song, and J. Liu, “Appropriate indoor operative temperature and bedding micro climate temperature that satisfies the requirements of sleep thermal comfort,” *Build. Environ.*, vol. 92, pp. 20–29, 2015.

[53] L. Lan, Z. W. Lian, and Y. B. Lin, “Comfortably cool bedroom environment during the initial phase of the sleeping period delays the onset of sleep in summer,” *Build. Environ.*, vol. 103, pp. 36–43, 2016.

[54] J. Du, M. Chan, D. Pan, and S. Deng, “A numerical study on the effects of design/operating parameters of the radiant panel in a radiation-based task air conditioning system on indoor thermal comfort and energy saving for a sleeping environment,” *Energy Build.*, vol. 151, pp. 250–262, 2017.

[55] C. Song, Y. Liu, and J. Liu, “The sleeping thermal comfort model based on local thermal requirements in winter,” *Energy Build.*, vol. 173, pp. 163–175, 2018.

[56] D. Zhao, J. Ji, H. Yu, and X. Zhao, “A study on thermal characteristic and sleeping comfort of a hybrid solar heating system applied in cold rural areas,” *Energy Build.*, vol. 182, pp. 242–250, 2019.

[57] E. A. McCullough, P. J. Zbikowski, and B. W. Jones, “Measurement and prediction of the insulation provided by bedding systems,” *ASHRAE Trans.*, vol. 93, pp. 1055–1068, 1987.

[58] Z. Lin and S. Deng, “A study on the thermal comfort in sleeping environments in the subtropics-Developing a thermal comfort model for sleeping environments,” *Build. Environ.*, vol. 43, no. 1, pp. 70–81, 2008.

[59] T. Hoyt, S. Schiavon, A. Piccioli, D. Moon, and K. Steinfeld, “CBE thermal comfort tool,” *Cent. Built Environ. Univ. Calif. Berkeley <berkeley. edu/comforttool.> (Feb.*, 2013.

[60] S. S. Shapiro and M. B. Wilk, “An analysis of variance test for normality (complete samples),” *Biometrika*, vol. 52, no. 3/4, pp. 591–611, 1965.

[61] Y. H. Yau and B. T. Chew, “Thermal comfort study of hospital workers in Malaysia,” *Indoor Air*, vol. 19, no. 6, pp. 500–510, 2009.

[62] S. Sattayakorn, M. Ichinose, and R. Sasaki, “Clarifying thermal comfort of healthcare occupants in tropical region: A case of indoor environment in Thai hospitals,” *Energy Build.*, vol. 149, pp. 45–57, 2017.

[63] F. Azizpour, S. Moghimi, C. H. Lim, S. Mat, E. Salleh, and K. Sopian, “A Thermal Comfort Investigation of a Facility Department of a Hospital in Hot-Humid Climate : Correlation between Objective and Subjective Measurements,” *Indoor Built Environ.*, vol. 22, no. 5, pp. 836–845, 2013.

[64] I. D. Griffiths, *Thermal comfort in buildings with passive solar features: field studies*. Commission of the European Communities, 1991.

[65] F. Nicol, M. Humphreys, and S. Roaf, *Adaptive thermal comfort: Principles and practice*. 2012.

[66] M. Vellei, M. Herrera, D. Fosas, and S. Natarajan, “The influence of relative humidity on adaptive thermal comfort,” *Build. Environ.*, vol. 124, pp. 171–185, 2017.

[67] F. Nicol and M. Humphreys, “Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251,” *Build. Environ.*, 2010.

[68] M. Indraganti and D. Boussaa, “An adaptive relationship of thermal comfort for the Gulf Cooperation Council (GCC) Countries: The case of offices in Qatar,” *Energy Build.*, vol. 159, pp. 201–212, 2018.

[69] H. B. Rijal, M. Honjo, R. Kobayashi, and T. Nakaya, “Field investigation of Comfort Temperature and Adaptive Model in Japanese Houses,” in *Architectural Science Review*, 2013, vol. 56, no. 1, pp. 54–69.

[70] S. A. Zaki, S. A. Damiati, H. B. Rijal, A. Hagishima, and A. Abd Razak, “Adaptive thermal comfort in university classrooms in Malaysia and Japan,” *Build. Environ.*, 2017.

[71] M. Indraganti, R. Ooka, and H. B. Rijal, “Thermal comfort in offices in summer: Findings from a field study under the ‘setsuden’ conditions in Tokyo, Japan,” *Build. Environ.*, vol. 61, pp. 114–132, 2013.

[72] M. R. Sharma and S. Ali, “Tropical Summer Index-a Study of Thermal Comfort of Indian Subjects,” *Build. Environ.*, vol. 21, no. 1, pp. 11–24, 1986.

[73] Y. Yau and B. Chew, “Adaptive thermal comfort model for air-conditioned hospitals in Malaysia,” *Build. Serv. Eng. Res. Technol.*, vol. 35, no. 2, pp. 117–138, 2013.

[74] F. Nicol and S. Roaf, “Pioneering :new indoor temperature standards" the Pakistan project,” *Energy Build.*, vol. 23, pp. 169–174, 1996.

Evaluating the suitability of standard thermal comfort approaches for hospital patients in air-conditioned environments in hot climates

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Highlights

- Thermal sensation votes (TSV) were highly overestimated predicted mean votes (PMV) of all patient groups, suggesting that a warmer environment is desired.
- Statistically significant differences (t = 6.780, *p-value* < 0.000) were detected between the TSV and PMV of all patients and sub-groups by gender and wards.
- A wide range of neutral temperatures obtained by Griffith's method, showed the diversity of patients' medical conditions and their preferable temperatures.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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